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Analysis of damaged welds no. 111 in the PGV-1000 steam generator and damage repair proposals

V.P. Povarov*

Novovoronezh NPP, a Branch Department of JSC "Rosenergoatom Concern". 396072, Novovoronezh, Voronezh Region, Yuzhnaya 1 industrial estate, Russia

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Abstract

Reliability of complex facilities, such as nuclear power plants, under construction or in operation is fundamental to the safety of humans and the natural environment. The key reliability-related factors are absence of errors in structural design and calculations, proper selection of materials and the manufacturing technology, quality of the materials used and the onsite welding operations, conditions of operation and in-service inspection.

Despite the fact that much attention is given in the course of the NPP design and operation to ensuring reliability, the experience of operation has demonstrated that there is a potential for crack formation in welded joint No. 111 of the PGV-1000 M steam generator. The crack nucleation and growth mechanism has not been yet unambiguously identified.

This paper presents the results of a study into the causes for the metal damage in the region of welded joint No. 111 between the hot header and the steam generator vessel's nozzle of Dn1200.

Keywords: Discontinuity; Steam generator (SG); Welded joint; Experimental research.

The reliability of the VVER-1000 NPP's main equipment, specifically in conditions of an extended service life, depends on the reliability of its individual components. The most critical item for theVVER-1000 steam generators (SG) is the welded joint between the primary coolant "hot" header and the steam generator vessel's Dn1200 nozzle (Fig. 1).

We shall consider the descriptions of recurring defects at nuclear power plants in Russia and Ukraine that manifest themselves as "cracks and discontinuities in the metal of welded joint No. 111 between the primary circuit header and the SG vessel" in the period of 1996 through 2013 (as of 2013) [1].

A through-the-thickness defect was detected in welded joint (WJ) No. 111 between the "hot" header and the SG allowance area at unit 1 of South-Ukrainian NPP during the 2001 preventive repair operations on SG-2. A non-through crack of the length 315 mm was detected at South-Ukrainian NPP's unit 2 during an ultrasonic (US) inspection of WJ 111 between the hot header and the SG-1 vessel, extending throughout the central portion of the Dn850 MCP bend. Inadmissible discontinuity flaws were detected in the WJ between the primary circuit "cold" header and the Dn1200 nozzle at unit 2 of Zaporozhye NPP during an US inspection of SG-2's WJ 111 in the course of the 2010 preventive repair operations. During a scheduled US inspection of WJ 77/1 in 1SG-3, using TsNIITMASh's methodology, in the period of the preventive maintenance at unit 1 of Kalinin NPP in 2006, discontinuity flaws of the length ∼400 mm were detected along the WJ at a depth of up to 30 mm from the outer surface. An additional "manual" inspection of WJ 77/1's defective area proved that the discontinuity existed.

The presence of black loose deposition with a thickness up to 20 mm was detected at the defect point by a visual examination of the "cold" header "pocket". In the period of a medium repair at unit 2 of Balakovo NPP in 2006, a discontinuous chain of flaws was detected during a scheduled US inspection of the metal in 1SG-1's WJ, using TsNIITMASh's methodology, in the form of four areas of the length 20 to 30 mm each (total length ∼470 mm) and of the width ∼30 mm, extending along the WJ, at a depth of 45 to 50 mm from the outer surface. No inadmissible defects were detected during the inspection of the same joint by the Avgur 4.2 automated US inspection system. An additional "manual" US inspection of the defective area in SG-1'sWJ

* Corresponding author:

E-mail address: PovarovVP@nvnpp1.rosenergoatom.ru.

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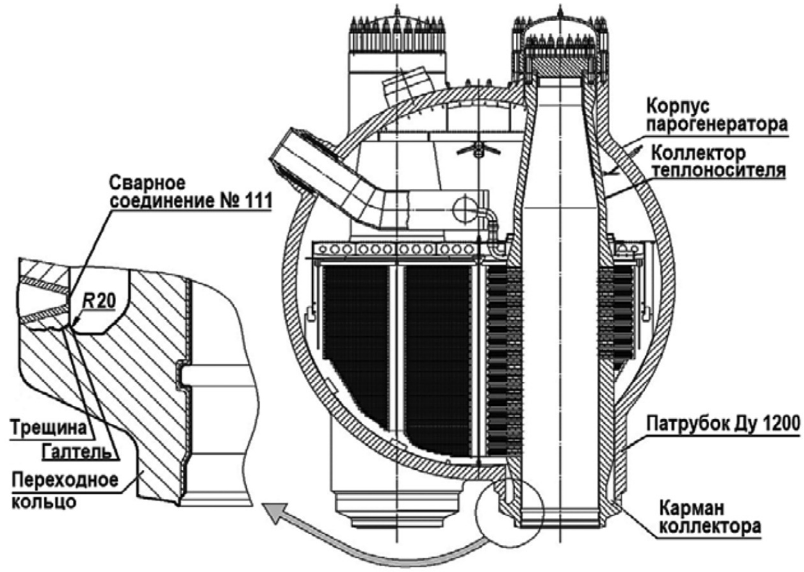


Сварное соединение № 111 = Welded joint 111
Корпус парогенератора = Steam generator vessel
Коллектор теплоносителя = Coolant header
Трещина = Crack
Галтель = Fillet
Переходное кольцо = Adapter ring
Патрубок Дн 1200 = Dn1200 nozzle
Карман коллектора = Headerpocket

Fig. 1. PGV-1000 M steam generator.

111-1 was conducted to update the US test results. It was confirmed that discontinuity flaws existed. After the measurement error was eliminated, another inspection was conducted using the Avgur 4.2 system based on the Avgur AUSI method. The inspection revealed discontinuity flaws of the size exceeding the permissible quality assessment standards under PNAE G-7-010-89.

A review into the experience of operation of Novovoronezh NPP's unit 5 shows that there were major damages around WJ 111 in all four SGs [2]. The defects are found in the radius blend between the pocket and the metal of WJ 111-1.

During the period of operation, defects were detected in WJs111-1 on the following SGs: 5SG-1 in 1998 and in 2004; 5SG-2 in 2007; 5SG-3 in 2001; 5SG-4 in 2007 and in 2009, and 5SG-1 in 2013. The unit was in a "hot" state at 10:20 am on 6 June 2013 with the outage program being under way as part of the 2013 preventive repair. A steam leak was detected during the equipment inspection from beneath the thermal insulation in the region of the "hot" header in the bottom part of 5SG-1's vessel. A 25 mm long crack with a through-the-thickness defect, having an angle of $\sim 45°$ to the weld axis, was detected at 7:30 am on 08.07.2013 as the result of a visual and liquid penetrant examination. After the reactor was brought into a cold state and thermal insulation was removed, a leak was detected at 10:40 the same day near WJ 111 of 5SG-1's "hot" header.

The 5SG-1 steam generator was commissioned in September 1989. Its operating time to the defect detection was 24 years. The component was in repair in 1998 and 2005 and welding was used in areas of the length 575 and 285 mm respectively. The component was tested nondestructively as part of the 2012 preventive repair.

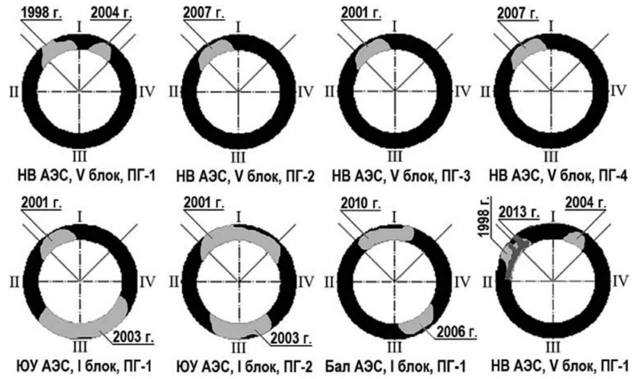
Crack-like discontinuity flaws in excess of the rejection level were revealed by a US inspection and an automated US inspection. The discontinuity flaws were located in the WJ area of 510 mm long.

Fig. 2 presents a graphic illustration of the recorded damages to the critical joint, namely the region of the SG hot header welding to the MCP nozzle (WJ 111). Rather long and high crack-like defects,including through-the-thickness defects, have been detected by now in nine SGs of the VVER-1000 NPPs.

As shown by the figure, the initial damage area is directed in all cases towards the MCP hot leg as seen from the short generatrix of the nozzle near the area with the greatest mechanical damage.

During the initial damage, the main crack is directed along the weld and has a great deal of crack kinking. Further defects of the same welds looked differently: there were five knife-like cracks along the nozzle axis (across the weld) on the side opposing the initial defect.

The defect of WJ 111 was caused by corrosion damage to the metal due to intensive corrosive processes resulting in the corrosion pit formation, the effects from heavy tensile loads in the fillet region, and the transcrystalline crack propagation in the



НВАЭС = Novovoronezh NPP
блок = unit
ПГ = SG
ЮУ АЭС = South-Ukrainian NPP
Бал АЭС= Balakovo NPP

Fig. 2. WJ 111 defect areas: I – short generatrix of theDn1200 nozzle; II – long generatrix of the Dn1200 nozzle; III – generatrix of the Dn1200nozzle (that nearest to the "hot" bottom); IV – generatrix of the Dn1200nozzle (that nearest one to the "cold" bottom).

metal up to the through-the-thickness defect formation after it developed and achieved critical dimensions.

The solution to the problem of the WJ 111 cracking in steam generators at the VVER-1000 NPPs is one of the top priorities in the activities to improve the unit operation safety during the extended life period. This problem is defined by a combination of temperature conditions, mechanical and corrosion impacts, is challenging and has not been solved to date.

The following structural and operating features of the welded joint between the header and the Dn12900 nozzle can be identified:

- a complicated design of the header welding joint;
- a simultaneously complex thermal-power operating impact from the primary and secondary circuit coolant;
- a stagnant are at the defect point (a corrosively aggressive medium in the pocket);
- heat-strain aging of the material.

A review into the cases involving in-service damages to WJ 111 has shown that:

- the detected degree of the actual operating loading and the potential levels of residual stresses in the crack nucleation and progression region are relatively low;
- the failure starts in the parent metal in the fillet region and extends throughout the thickness of the item while propagating up through the weld metal;
- the "pocket" region has unfavorable water chemistry (sludge formation);
- a similar failure mechanism –joint action of delayed strain-corrosion cracking (DSCC) and corrosion fatigue (CF);
- the failure is preceded by a prolonged incubation period;
- repair areas are the last to "crack".

Damage to the metal of the header – Dn1200 nozzle welded joint is immediately caused by the formation of multiple DSCC cracks as the result of stresses in the given joint, and by a combination of the MCP operating conditions, structural features and loading modes.

An attempt has been made in this study to analyze all root causes for the metal damage in the header – Dn1200 nozzle welded joint in the order of predominance. The top-priority factor is the secondary circuit water chemistry and the presence of corrosion deposits in the pocket area.

Until quite recently, the VVER NPPs had the secondary circuit water chemistry using corrective feedwater and condensate treatment by hydrazine-hydrate and ammonia. The secondary circuit fluid quality standards define requirements for the secondary circuit water quality, the restrictions on the unit operation when there are deviations of the SG feedwater and blowdown water quality indicators from the rated values, and the operating limit, as well as requirements to the scope and frequency of inspection, and to the secondary circuit water chemistry maintenance techniques.

To maintain the secondary circuit water chemistry, a salt compartment has been organized in the SG for blowdown with a flow rate of 10 to 15 t/h to remove soluble salts. Periodic blowdown with a flow rate of 15–20 t/h has been organized for the sludge removal from the SG vessel's lower generatrix, including from the SG "pockets".

Components of the condensate and feedwater line are known to contain copper-containing alloys due to which coppers and its oxides enter the steam generator together with feedwater, and deposits of these have been found in the header "pockets".

After a template was cut out from the welded joint between the "hot" header and the Dn1200 nozzle of 5SG-1 (a through leak) in the period of the 2013 preventive repair, deposit samples were taken from the annulus and the chemical composition of the deposit was determined [3].

Table 1
Composition of deposits in the annulus.

Indicators, %								Water extract pH value, units
Fe_2O_3	CuO	SiO_2	CaO+ MgO	Cl	SO_4	Na	H_3BO_3	
85.2	3.1	2.9	2.2	0.04	0.092	0.056	-	6.3

Loose deposits consist of small brown-colored plates. According to the visual examination results, the deposits from the annulus looked identically to the deposits from the secondary side steam generator's heat-exchange surface.

The amount of the deposits removed from the annulus in the template cutting area is 4.5 kg. The chemical composition of the deposits is presented in Table 1.

The feedwater quality achieved in foreign NPPs, where corrosion-resistant alloys are used as the material for the condensate and feedwater lines, is known to be higher by an order of magnitude than that achieved in Russian units.

A major problem in maintaining the VVER NPP secondary circuit water chemistry is deposition control inside steam generators, and another important task is to reduce the rate of corrosion of all structural materials. And the permissible rate of corrosion is what defines the equipment life, which specifically depends as well on the concentration of corrosion products as the major feedwater impurities.

The peculiarities of water chemistry also require that perlite steels, austenitic stainless steel and copper-containing alloys, having different corrosive stability in fluids, to be used as materials for the secondary circuit components.

The most vulnerable secondary circuit component is the SG in which ionogenic impurities, coming in with feedwater, concentrate due to the boiler water evaporation. It is exactly the corrosive problems of the secondary circuit and the impossibility to maintain the optimum pH values in the SG feedwater and in two-phase fluids that has caused alternative additives to be searched for to adjust the pH value in the secondary circuit as a means of extending the steam generator life [4].

The measures developed and implemented in recent years to improve the secondary circuit water chemistry, including corrective treatment of the secondary circuit fluid by lithium hydroxide, morpholine and ethanolamine, along with the increase in the density of the turbine condensers and the condensate line's vacuum portion, and introduction of automatic chemical control, are expected to have a pronounced effect on the process of the deposit formation on the SG heat-exchange surfaces and of the deposit buildup in the SG pocket.

Morpholine is slightly aggressive to copper-containing alloys. The morpholine-based water chemistry in Rostov NPP unit 2's secondary circuit makes it possible to reduce the amount of corrosion products entering the steam generators by about 200 to30 to 60 kg for the fuel life per one steam generator, and to improve the entrainment of iron with the SG blowdown water thanks to the loosening of earlier deposits as the result of the morpholine effect, this leading to a reduction in the contamination of the steam generator metal surface, and, consequently, to a decrease in the risk of corrosion.

Table 2
Specific contamination of the SG tube bundle at unit 5.

Year	Specific contamination, g/cm^2			
	SG-1	SG-2	SG-3	SG-4
2006	< 20			
2007		<20		
2008				< 20
2009			< 20	
2010				
2011	< 20	< 20		
2012			< 20	< 20

A recent substitution to the morpholine water chemistry is ethanolamine water chemistry theoretically justified and practically tested for the PWR reactor secondary circuit. In Russia, this water chemistry was introduced at unit 2 of Balakovo NPP in 2007 [5]. Since the introduction of ethanolamine water chemistry, the content of copper in deposits on the SG's heat-exchange surface has decreased by a factor of 3.3. It is shown in [5] that the substitution of the NPP secondary circuit hydrazine-ammonia water chemistry for ethanolamine water chemistry has led to a greatly decreased erosion and corrosion wear of essential secondary circuit components.

Following the 2010–2011 preventive repair, ethanolamine water chemistry is being introduced in the secondary circuit at unit 5 of Novovoronezh NPP. With this chemistry, the criterion for chemical washing to be undertaken is the specific contamination of the tube bundle to 100 g/m^2 and more detected by the SG corrosion inspection. Table 2 presents the results of the SG tube bundle specific contamination inspection at unit 5 [6] (at such points as defined by the operating instructions of Gidropress design bureau).

No special chemical washing of the annuli is required by the secondary circuit water chemistry standard and design documentation, while the design SG blowdown pattern fails to ensure the efficient sludge removal from the header "pockets".

Steam generators have been chemically washed at unit 5 since 1997, as required by the working programs developed based on regulatory documents. The washing frequency of once in four years was defined by the standard "Water Chemistry of the VVER-1000 NPP Secondary Circuit. Fluid Quality Regulations and Compliance Tools". The annuli were washed simultaneously with the tube bundle washing.

Table 3 presents data on the quantity of washed-off deposits (in kg) for 1977–2011.

The most radical of the current techniques to prevent corrosive wear of the SG heat-exchange tubes and to remove sludge deposit from the SG pockets is periodic SG washing from the secondary circuit side.

Given the requirement for the contamination removal from the header "pockets", Gidropress design bureau has developed and tested the SG flushing device which is inserted through a nozzle into the header "pocket" and washes off deposits when

Table 3
Quantity of deposits (in kg) washed offduring the SG washing at Novovoronezh 5.

Year	SG-1	SG-2	SG-3	SG-4	Year	SG-1	SG-2	SG-3	SG-4
1997			500		2005				
1998	600				2006	330			
1999		800		1000	2007		480		
2000					2008				800
2001			800		2009			500	
2002	400				2010				
2003		600			2011	1230	580		
2004				750					

the unit is shut down, since the design blowdown system does not ensure efficient entrainment of deposits from the annulus.

The device has proved to be efficient by field tests at Novovoronezh NPP's unit 5 [7]. The use of special flushing devices has helped to remove "traces" of deposits from inside the "hot" header "pocket" after the chemical washing.

The results of the DSCC process investigations at JSC TsNIITMASh [8,9] have shown that quasibrittle DSCC-type failure of specimens was recorded during tensile tests in conditions of the working surface contact with sludge (75% Fe_2O_3+ 25% CuO). The crack growth rate was $7 \cdot 10^{-6}$ mm/sor 221 mm/g. Ductile failure of specimens and no DSCC was recorded during tensile tests in conditions of the working surface contact with sludge with a CuOP content of less than 10%. No crack undergrowth was observed during tests with sludge (75% Fe2O3+25% CuO) on compact 20 mm thick specimens with an initial fatigue crack at a constant load other than causing ductility in metal.

A conclusion may be made based on the results obtained that no DSCC is observed when the copper oxide concentration in deposits is below 10%. When the level of tensile stresses in metal is below the yield point (even when the copper oxide concentration is sufficient for DSCC), no DSCC is observed as well.

Corrective activities needed to exclude damage to WJ 111 include the following: substitution of the NPP secondary circuit hydrazine-ammonia water chemistry for morpholine or ethanolamine water chemistry; the SG header pockets shall be chemically washed during each preventive repair rather than once in four years; the metal in WJ 111-1 and WJ 111-2 of the steam generators shall be inspected by visual examination, penetrant tests and ultrasonic testing methods, as well as by phased-array method as part of the preventive repair operations at the unit; replacement of the TPN condensers and main condensers for condensers with stainless-steel tubing.

Damage to WJ 111 is caused by electrochemical corrosion of the metal under the action of corrosively active impurities in water.

For units operating in the extended life conditions, it is required to introduce corrective measures to reduce the operating process effects on the dynamics of damageability in two ways:

- a reduction in the corrosive factor effects on damageability (introduction of the pocket passivation technology and a reduction in the level of impacts from electrochemical corrosion);
- optimization of operating conditions affecting the actual loading level for WJ 111 in the steam generators off the VVER-1000 NPPs.

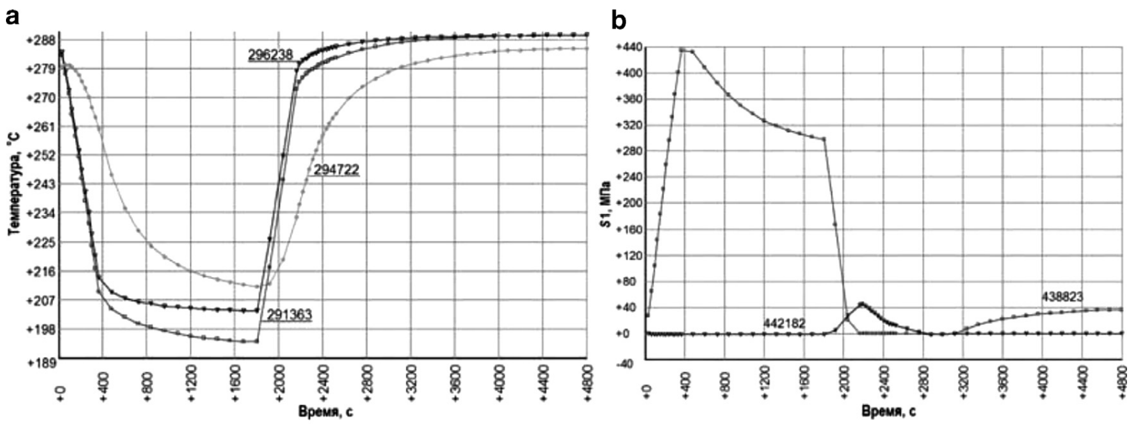
It has been determined as the result of monitoring the heat-strain loading of WJ 111 that the reactor transients (heat-up, cooldown) involve non-steady-state temperature processes inside the header "pocket", and beyond-design-basis thermal "shocks" have been recorded [10], leading to high beyond-design stresses, which is confirmed by results of field strain-gage tests by a continuous in-service damageability monitoring system (CIDMS).

An analysis of the 2011 and 2012 monitoring data shows that all of the temperature anomalies were taking place when the blowdown system was not active. And the most dangerous anomalies during the reactor operation were recorded at working parameters when non-steady-state heat-stress load were superimposed on operating loads. The data obtained allows demonstrating the overall scenario of how temperature anomalies arise: the SG blowdown is not active, all SGs are interconnected through the periodic blowdown header, there is no flow in the blowdown lines of Dn20 andDn8, the water therein is gradually cooled down (5–10 °C/h), and the amount of "stagnant" water in the blowdown pipeline of one SG is about 1–2 m^3. When the pressure is increased in one of the SGs, the chilled water is transferred by pressure into the other SG with a lower pressure via the blowdown lines, and a thermal shock takes place in the region of WJ 111. It is shown in [2] that the highest stress concentration factor is in the fillet radius transition area.

Fig. 3 shows temperature and stress variations in the pocket fillet during a thermal shock [2]. A simulation of the temperature conditions in the region of WJ111 with different temperature variation rates in the fillet area has shown that, at high rates, the material life may be shortened by 10.7% for 1000 cycles only thanks to temperature anomalies.

The fatigue version of crack formation [11] explains the delayed brittle stepped mechanism of the metal failure in WJ 111 as the result of the loading sequentially by three loads: from vibration (long-term load), from rigid low-cycle load (temperature compensation) and periodic loads. Rare high-stress cycles cause small vibration-induced microcracks to join and to form gradually (in the course of several years) the main crack beneath the SG bottom at the torsional (tangential) stress concentration point. Such pattern of the defect development in the region of WJ 111 is fairly well described in the statement of TsNIITMASh [12]concerning the crack formation in the region of WJ 111.

What can be done to exclude beyond-design-basis thermal shocks resulting from the blowdown system operation? This requires the primary circuit hydraulic test procedures to be updated with altering the procedure for switching over the periodic blowdown headers and adding to the safe operation manual instructions on the valve opening (closure) in the periodic blowdown lines. This will lead to a reduced level of the operating heat-strain impacts on the metal of WJ 111 and to a decrease in the damageability level.



Температура = Temperature
Время, с= Time, s

Fig. 3. Thermal shocks in the pocket fillet area of WJ 111: (a) – temperature variation; (b) – stress variation.

Conclusions

1. An analysis into the malfunctions at the VVER-1000 NPPs makes it possible to state that actual risks of crack-like defect formation in the steam generator welded joints 111 arise after about 20 years of operation. As a rule, these emerge in the welded joints between the Dn1200 hot nozzles and the SG vessels.
2. One of the causes for the development of such defects is the presence of copper oxide deposits in the SG pocket.

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